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THESIS

EFFECTS OF ACOUSTIC INTERFERENCE
OF A FLOWING GAS ON ITS
ELECTRICAL POWER HANDLING CAPABILITIES

by

Jack W. Tucker

October 1982

Thesis Advisor: O. Biblarz

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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER	2. GOVT ACCESSION NO. AD-A125601	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) Effects of Acoustic Interference of a Flowing Gas on its Electrical Power Handling Capabilities		5. TYPE OF REPORT & PERIOD COVERED Master's Thesis; October 1982
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Jack W. Tucker		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Naval Postgraduate School Monterey, California 93940		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS Naval Postgraduate School Monterey, California 93940		12. REPORT DATE October 1982
		13. NUMBER OF PAGES 36
14. MONITORING AGENCY NAME & ADDRESS(If different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, If different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Acoustic Excitation
Electrical Discharge Lasers
Acoustically Generated Turbulence

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

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Justification

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Availability Codes
Avail and/or
Dist   Special

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by

Jack W. Tucker
Lieutenant, United States Navy
B.S., University of Nebraska, 1975

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN AERONAUTICAL ENGINEERING

from the

NAVAL POSTGRADUATE SCHOOL
October 1982

Author: _____

Approved by: _____
                                              Thesis Advisor
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           _____
                     Dean of Science and Engineering

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ABSTRACT

This work explores the feasibility of enhancing the electrical handling capabilities of a flowing gas by means of acoustically generated disturbances. Air flowing between electrodes, which are mounted perpendicular to the flow, is excited by acoustic drivers, mounted on two sides of a test section, in an attempt to increase the glow-discharge power input to the electrodes prior to breakdown and subsequent arcing.

Although equipment failure precluded obtaining the desired results, lessons learned regarding flow rate, power required, and test section size, encourage further experimentation in this area. Careful consideration to obtaining an optimum Strouhal number with regards to the acoustic excitation appears desirable.

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I. INTRODUCTION AND BACKGROUND

Much research is being conducted in the area of laser technology. Lasers are being developed for use in all facets of life, both in military and non-military applications. For military applications, high-powered lasers are of great interest and much work has been spend on ways to improve efficiency and output power capabilities.

In order for a laser to operate, three basic conditions must be satisfied [Ref. 1]. There must exist an active medium, or a collection of atoms or molecules which will emit radiation in the optical range of the electro-magnetic spectrum. There must be a population inversion of the atoms in the active medium, and there should be some sort of optical feedback present in the system to sustain the lasing phenomenon.

The workhorses of the laser industry have been the electrically pumped, gas lasers. Specifically, the helium-neon atomic gas laser attains a population inversion, or is pumped by placing a high voltage across the gas filled cavity. The higher the voltage applied, the higher the pumping rate, and therefore, the greater the output of the laser. This relation between the voltage applied and the output of the laser would lead one to believe that the output is limited only by the electrical potential available to the input

electrodes, but this is not the case. As the voltage across the electrodes is increased a point is achieved where the gas medium breaks down, and allows "arcing" to occur between the electrodes. This, of course, collapses the power into the active medium, and the lasing action ceases through most of the volume.

There have been numerous experiments conducted which prove the merits of flowing the gas medium through the cavity as well as of creating turbulence within the flow. Both of these have the effect of raising the power handling capability of the gas medium significantly. Most recently, Wainionpaa [Ref. 2] showed the effects of increasing flow with and without turbulence, both in a cross flow and parallel flow configuration of the electrodes. His method of inducing turbulence into the flow was a physical grid placed in his test section upstream of the electrodes. These results were verified in the work reported in Appendix A. A more efficient means of causing turbulence might be to use some sort of outside interference such as sound. The advantage of this method appears to be that there would be no physical blockage of the gas flow which would decrease the pressure drop through the test section. This, in turn, would decrease the required input flow pressure. By inducing sound into the flow the capability of introducing pure sinusoidal interference becomes possible instead of the "white" noise introduced by physical grids. The frequency of the excitation may also be easily varied, and the capability

of superimposing various frequencies could enhance further the utility of this technique.

There have been many efforts to examine flow disturbances caused by acoustic waves in a gas, but few of the studies were concerned with the specifics of the sound required to cause turbulence, and none of the studies examined the power handling capabilities of the acoustically disturbed gas.

As early as 1858 there was a scientific curiosity about the acoustic sensitivity of gas jets. Leconte [Ref. 3] noticed that the flame-jet from coalgas jumped in response to certain notes played from a cello. His observations led him to remark that jets must be musically inclined. This phenomenon was first known as the sensitive flame, but Tyndal showed that combustion was completely inessential, and that the phenomenon could be observed in any gas jet given suitable conditions. As early as 1879 Rayleigh introduced stroboscopic illumination and analyzed the instability problem.

In 1960 Hiroshi Sato [Ref. 4] made a study of the transition of a two-dimensional jet. The response characteristics of laminar jets to external excitation were investigated in detail by using sound as the exciting agent. He found that the effects of the excitation was quite remarkable when the frequency of the excitation coincides with that of the self excited sinusoidal fluctuations.

Freymouth, in 1965 [Ref. 5], introduced artificial disturbances via sound from a loudspeaker into the boundary

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layer of a jet. The growth of the disturbances in the boundary layer was investigated by a hot-wire anemometer technique. His experiments showed that velocity fluctuations contained higher harmonics of the sound frequency which depended in a complicated manner on the position of the hot-wire probe in the layer.

In 1968 Becker and Massaro [Ref. 6] used sound from a loudspeaker pointed at the nozzle of a jet. They found a marked acoustic selectivity at Reynolds numbers below 10,000, with the intensity of the exciting tone showing no visible effect above a certain level. At a critical frequency, the jet flared near its roots, and the initial angle of spread as much as doubled. The points of appearance of ring vortices and of turbulent breakdown moved closer to the nozzle. The dominant frequency was never ambiguous. There were discrete resonant frequencies found, which gave a discontinuous relation between the frequency of the most highly amplified disturbance and the nozzle velocity. They concluded that this was due to the resonances of the nozzle chamber. The sensitivity of the jet to applied acoustic excitation was most acute at nozzle Reynolds numbers below 7600. At higher Reynolds numbers the disturbance pattern was spotty and the response was very much weaker.

Crow and Champagne [Ref. 7] used a loudspeaker to study the orderly structure in jet turbulence. They showed that the effect of a loudspeaker on the turbulence very much

depended on the Strouhal number of the excitation, where

$$St = f \times D / Ue$$

and f is the frequency of excitation, D is the characteristic length of the cavity, and Ue is the exit velocity of the gas. They found that, with D constant and f an integer multiple of the cavity resonant frequency, if the exit velocity was varied to maintain a Strouhal number of 0.3, the excitation had the most dramatic effect on the flow. They also found that the turbulence intensity peaked at a distance $x / D = 4$ downstream of the driver.

In 1974 Miksad [Ref. 8] built a small turbulence tunnel and mounted a loudspeaker on the side of the test chamber. He then did an experimental study of the instability and transition of a laminar-free shear layer by sound excitation. He found in his experiments that transition from laminar instability to turbulent breakdown covered approximately five wavelengths of the excitation frequency downstream.

In 1975 Bechert and Pfizemaier [Ref. 9] studied the amplification of broadband jet noise by pure tone excitation. During their experiments they were able to generate the most noise amplification when the Strouhal number was about 0.48. Moore, in 1977 [Ref. 10] very closely agreed with this after his study of the role of shear layer instability waves in jet exhaust noise showed that excitation at a Strouhal number of 0.5 caused the most turbulence.

Kibbens [Ref. 11] built a somewhat unique system to study the "Discrete Noise Spectrum Generated by an Acoustically Excited Jet". He injected sound at the nozzle exit through a peripheral exciter chamber which was driven from a loudspeaker enclosure, connected to the exciter chamber through flexible tubing. The exciter chamber was divided into four segments, each driven from an individual supply hose azimuthally coherent pressure wave at the exciter chamber exit. By measuring the sound pressure level in the flow downstream of the nozzle exit he determined that a Strouhal number of 0.45 produced the highest peaks.

II. EXPERIMENTAL APPARATUS

There are two main parts of the experimental apparatus: the flow system which developed the flow of air through the discharge gap; and the high voltage discharge circuit which developed the electric field between the discharge electrodes, and provided a means of measuring the voltage and current through the discharge.

A. FLOW EQUIPMENT

The flow system used was the same as was designed for research in Ref. 12 and subsequently used in the work of Refs. 13, 14, 15, and 2. Modification for the present research included discarding the turbulence generating screens, and configurating the test section with inserts to mount acoustic drivers flush with the inside of the test section, facing the cavity electrodes from opposite sides (Figure 1).

The flow system consists of an air compressor, a water-cooled heat exchanger, flow rate control valves, a plenum chamber, and a converging nozzle to the test section. The air is exhausted directly to the atmosphere from the constant area test section. Figure 2 shows the test section schematically. The air is supplied by a three stage Carrier centrifugal compressor with a 4000 cubic feet per minute capability at two atmospheres maximum pressure, through a
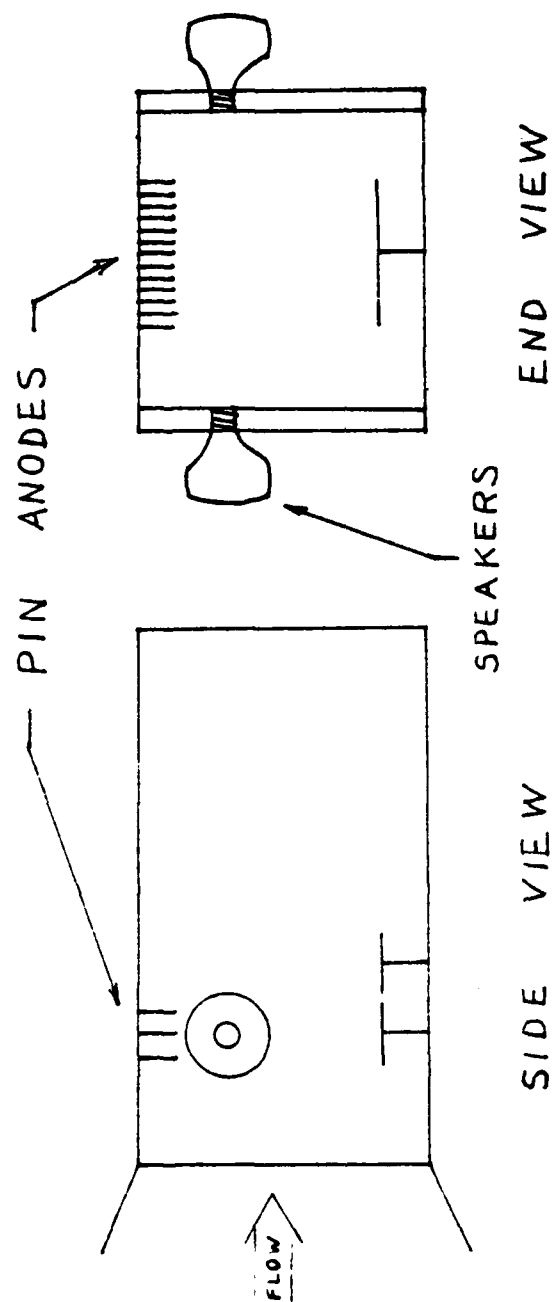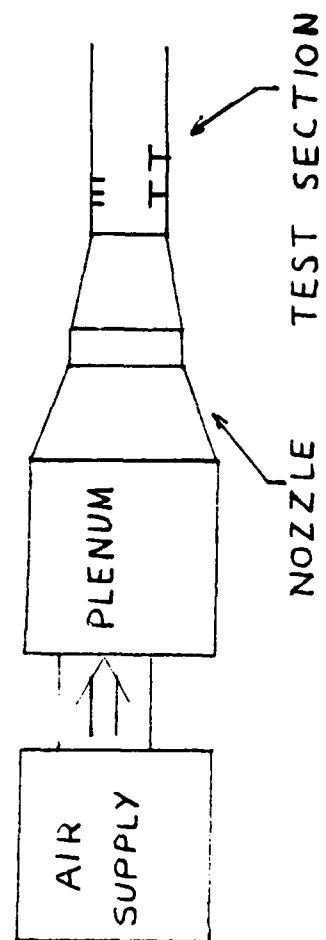
Figure 1. Test Section.

Figure 2. Flow System.

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water-cooled heat exchanger which maintains flow temperature at approximately 90 degrees Fahrenheit through an impact-type water and particle separator. Flow can be regulated by three gate valves. Flow velocities to 100 meters per second are obtainable.

The air flow was measured by a pitot static probe inserted in the exhaust opening of the test section.

B. DISCHARGE CIRCUIT

The discharge circuit consists of a high voltage power supply, high voltage leads, current and voltage instrumentation, the pin rack anodes and the cathode.

Power is supplied to the pin anodes by a Universal Voltronics Labtrol Model BA50-70 which provides up to 50 kilovolts and 70 milliamperes direct current. The control unit for the power supply incorporates a voltmeter and an ammeter to monitor the output. It is internally regulated and limited to break the circuit when either the output voltage exceeds a pre-set voltage or the current becomes excessive.

The pin-anode section consists of three rows of stainless steel pins, thirteen in each row, all connected in common. The pins are 0.875 inches long and 0.25 inches apart in each row. The rows are 0.5 inches apart. This pin-anode rack is mounted in the top of the test section pointing downward (Figure 1).

The two cathode plates are constructed of stainless steel, 2.22 x 4.44 inches in size. They are mounted in the bottom of the test secton side by side on the same horizontal plane, one directly under the pin-anode section, the other slightly downstream. The two cathodes are electrically insulated from each other. Provisions are made to allow movement of the cathodes up or down in order to change the physical distance from the pin-anodes.

For measurement purposes the output from the cathodes is fed through a precision 20 kilohm resistor, across which is connected a Textronic Model 555 Oscilloscope, and a Weston Model 931 Micro-ammeter is placed in series with this load. Excitation to the flow is provided by a Hewlett Packard Model 200CD signal generator. The variable frequency output of the signal generator is fed into a Citation II, 50 watt/channel dual-channel amplifier. The output of the amplifier is coupled to driver units which are mounted in the side walls of the test section (Figure 1). The driver units used for these experiments are Altec Model ID30C-16, rated at 30 watts (Figure 3). A Hewlett Packard Model 3400A RMS voltmeter is used to measure the voltage applied to the i put of the driver unit, for the purpose of recording the power needed to obtain various levels of excitation. This output system is depicted schematically in Figure 4.
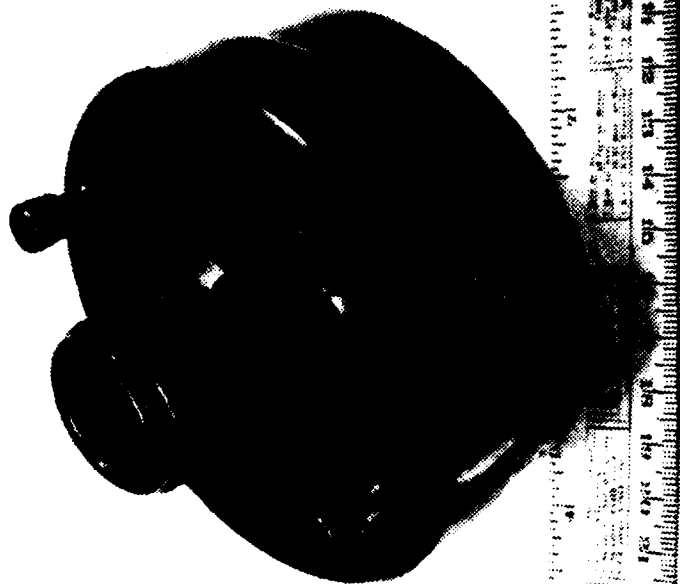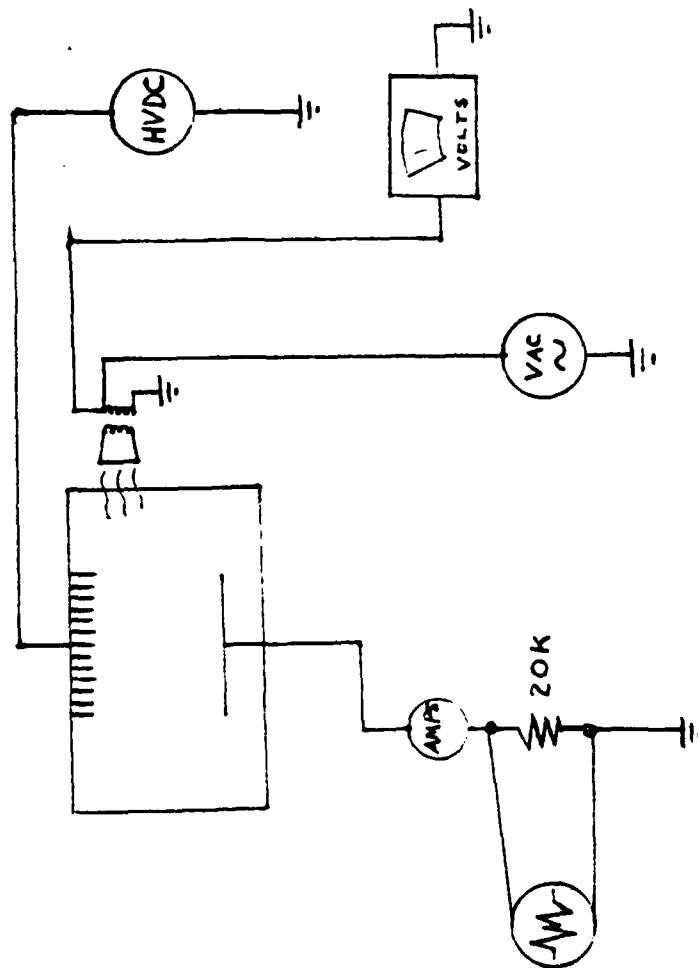
Figure 3. Acoustic Driver.

Figure 4. Discharge Circuitry, Second Cathode.

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III. NATURE OF THE PROBLEM

As stated earlier, previously conducted research
utilizing acoustic excitation of a flowing gas was mainly
concerned with the nature of the flow itself, and some of
what form the excitation should take, i.e., what intensity
and frequency best works for exciting the flow. Virtually
all of the previous works were concerned with turbulence
along the boundary layer, and what effect the acoustics had
upon that turbulence.

In this research the question to be answered is how
much can the electrical power handling capabilities of
the flowing gas be altered by the acoustically excited
turbulence throughout the entire flow around the pin
anodes. This problem took on two phases: determine how
much sound was required to initiate the turbulence, and
how much would this disturbance change the electrical
power handling capabilities of the gas. Once these
questions were answered we would have some ideas of how
efficient this power enhancement idea might be.

IV. METHOD OF INVESTIGATION

As depicted in Figure 1, the test section was mounted
with two speakers, one on each side, with the cone section
threaded into holes which had been drilled for mounting.
The cone of each speaker was made to sit flush with the
inside surface of the side panels so as not to physically
disturb the flow of air. The sound has directed at the area
of the pin-anodes in order to initiate "turbulence" around
the area of most interest. This idea of positioning the
speakers directly at the pins may have contributed to the
unsatisfactory results to be discussed later.

With the test section set up as described, the procedure
was to position a Kulite pressure probe in the end of the
section downstream of the pin-anodes. Under no-flow condi-
tions, inputs to the speakers of various frequencies and
intensities would be measured through the probe on a
spectrum analyzer. In doing so, the probe may be calibrated
for turbulence measurement as a function of power applied to
the speakers, and the optimum frequency, i.e., the cavity
resonant frequency, of the test section may be found by
observing which frequency displays the highest peak on the
spectrum analyzer.

If the probe position is varied across the width of the
section, a plot of the turbulence levels across the cavity

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for various frequencies may be obtained. This would be useful for focusing the noise at various positions in relation to the pin-anodes. This would enable investigation of the power handling characteristics as a function of where the sound was focused.

Once the optimum frequency is found and the probe has been calibrated, readings can be taken under flow conditions to determine the turbulence spectrum present for various flow rates.

Finally, the question at hand may be investigated. Two approaches may be taken to determine the effects of the turbulence within the flow; (1) apply a given voltage to the pin-anodes and measure the current flow into the cathode with no sound excitation present. Then apply the excitation frequency and observe the change of current through the cathode as a function of frequency, (2) for each flow condition measure the amount of voltage on the pin-anodes and the current through the cathode required to cause breakdown of the gas and arcing to occur. Then apply a given intensity and frequency of noise around the pin-anode area and remeasure the power required to cause arcing. The procedure is repeated for various frequencies and/or intensities to obtain a plot of the change in power versus turbulence spectrum applied to the pins at various flow rates.

V. RESULTS

Calculations were made (Appendix B) to approximate the resonant cavity frequency and the acoustic power required to cause turbulence within the flow of air. The calculated frequency was approximately 1.5 kHz, which turned out to be fairly close to the 1.37 kHz actually measured through use of the Kulite probe and spectrum analyzer.

The acoustic power required to cause turbulence enough to enhance the power handling capability of the gas was calculated to be about 50 watts.* Since no past work was found which created turbulence with sound except along a boundary layer, this calculation has not been verified.

During calibration of the Kulite Probe one of the speakers failed. This was thought to be due to power in excess of the 30 watts being applied at the input. During a second experiment using only one speaker, care was taken to limit the power into the speaker but it failed neverthe- less. Investigation into the cause of the failure led to the conclusion that the power applied to the speakers at a relatively pure tone was of intensity enough to cause the coil wire to burn out due to ohmic heating. Since the 30 watt

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*Private conversation with Prof. H. Medwin, Physics Department, Naval Postgraduate School, Monterey, CA, August 1982.

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power rating of the speakers was specified as a "pink noise"*
rating, the intensity of the sound allowed at any one frequency
is much less than that delivered by 30 watts of pure tone at
a discrete frequency. Time restraints prohibited reordering
of driver units in time for this report.

During the second run with just one speaker, a trial
attempt was taken at altering the current through the cathode
of the test section with an applied voltage to the pin-anodes
and an input to the driver unit varied in intensity and fre-
quency. This attempt proved fruitless as the current was not
appreciably affected by either a change in intensity or in
frequency of excitation. The same attempt was made at various
flow rates of the air with the same results. Due to subsequent
failure of the second driver unit, further investigation of
these findings has yet to be done. Several theories as to
why the results were poor can be formulated. Firstly, there
simply was not enough acoustic power available. As no horn
was utilized, the acoustic coupling might have been ineffi-
cient. It should be also noted that, during these runs, a
thin film of milar tape was placed over the driver cone.
This was to insulate the cone electrically from the pin-anode
discharge in the case of arcing occuring through the gas. It
was discovered in earlier experiments that, since the speaker
cone was physically closer to the pin-anodes than the actual

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*Noise whose spectrum level decreases with increased
frequency to yield constant energy per octave of bandwidth.

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cathode, the arcing would go from anodes to the speaker cone unless the milar tape was used. To protect the equipment against current surges, the tape was used and may have further attenuated the acoustic power going into the test section. The power from the speaker may have been inadequate due to the single tone output capability and/or the attenuation from the milar tape. Also, this trial attempt was made using only one driver because one had already failed. Better results may have resulted if two driver units been available.

Secondly, research shows [Refs. 7, 8] that when a boundary layer or jet stream was subjected to acoustic excitation the turbulence did not fully develop until the flow was a distance downstream of the excitation equal to several wavelengths of the excitation frequency. Since, in the present experiments, the effects of the excitation were measured precisely where the excitation was applied, the turbulence within the flow simply may have developed further downstream, lending to the desired effect not occurring. If the excitation were applied somewhere upstream of the pin-anode area, possibly enough turbulence would develop around the pins to give more favorable results.

Thirdly, several of the references show a correlation between desired effects of the acoustic excitation to the Strouhal number of that excitation. The physical significance of the Strouhal number is that it is a measure of the ratio of the excitation vibrational speed (frequency x characteristic distance) to the flow translational speed. Recall that

Becker and Massaro [Ref. 6] found that $St = 0.3$ worked best, Beckert and Pfizemaier [Ref. 9] found that 0.48 suited their experiments best, and Kibbens [Ref. 11] narrowed his results down to $St = 0.45$. The point is that for each of those cases a particular Strouhal number worked best. In our experiments the Strouhal numbers we were working with can be calculated easily:

$$St = fD/U_e$$

where $f = 1370$ Hz

$D = 4.44$ inches $= 0.37$ ft.

$U_e = 82$ ft/sec   (3.95" H_2O)

$St = 6.182$

or if $U_e = 98$ ft/sec.   (5.55" H_2O)

$St = 5.172$

These Strouhal numbers are obviously much higher than those found in previously reported experiments. Note that the flow rates in the previous works were on the order of Mach 0.3 or 0.4. Similar flow rates in our experiments would result in $St = 1.5$ since the flow was only at about Mach 0.075. This would indicate that either the characteristic length, D, or the excitation frequency, F, should be lowered. The excitation frequency, however, must be an integer multiple of the cavity resonance frequency, which is 1370 Hz, therefore it cannot be lowered below that value. The characteristic length could be shortened by building a new test section. This probably will be required due to the limited flow rate available to the existing system.

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Assuming that the flow rate may be increased to
120 ft/sec., in order to decrease the Strouhal number to
around 0.5 the characteristic length should be:

$$D = (0.5) \ (V)/ \ f$$

$$= 0.044 \ ft.$$

$$= 0.526 \ inches$$

Another possible solution might be to increase the
excitation frequency up to a point where the characteristic
length used was exactly the spacing between the pins in
the anode section.

VI. CONCLUSIONS AND RECOMMENDATIONS

Due to the equipment failure during the experiments, there was very little data available to analyze. Previous works do indicate, however, the feasibility of acoustic enhancement of the power handling characteristics of a flowing gas. The gas can be excited acoustically and the benefits of turbulence in the flow has already been proven.

In order to continue with these experiments it is recommended that more powerful speakers be made available. Also the ability to input over a wide band of frequency simultaneously might be helpful. This would enable more power to be input to the speakers without overdriving them with the intensity.

A test section which is smaller than the one used in these experiments appears to be desirable. Also, it is recommended that experiments be conducted to determine how far upstream of the anodes the excitation should be applied in order to develop the turbulence sufficiently around the anode area. In order to lower the Strouhal number of the excitation, which appears desirable, a higher flow rate must also be achieved.
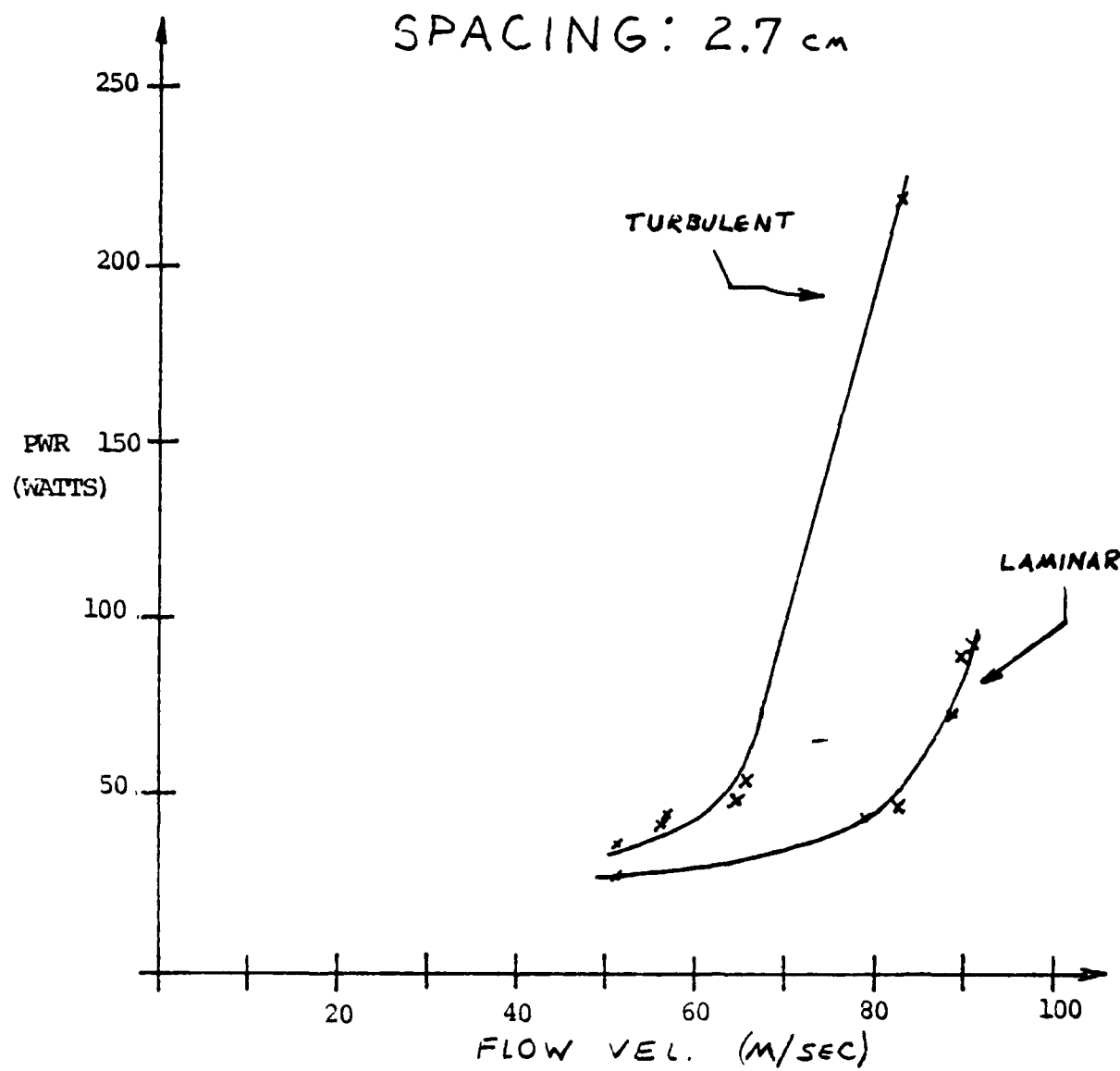
APPENDIX A

As a follow-on to previous thesis research [Ref. 2] the author conducted preliminary work involving the effects on power handling characteristics of a flowing gas due to increased flow rate of the gas and/or turbulence within the flow.
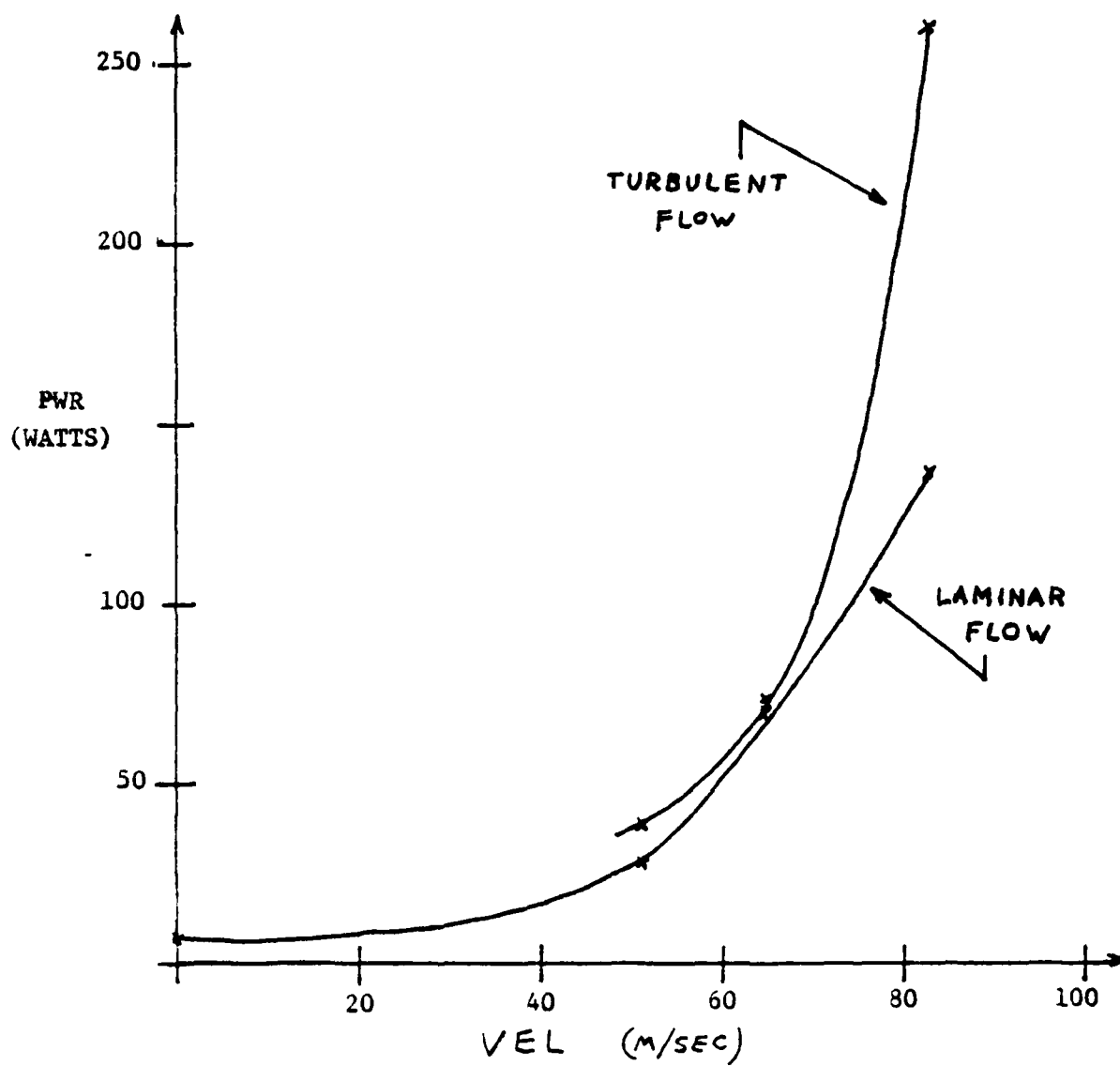
Voltage and current readings were recorded at various electrode spacings for numerous flow rates, both with and without turbulence. Turbulence was created within the flow by means of physical grids placed in the flow upstream of the electrodes. Input power versus flow rate was plotted for three separate electrode spacings (Figures A1, A2, and A3).
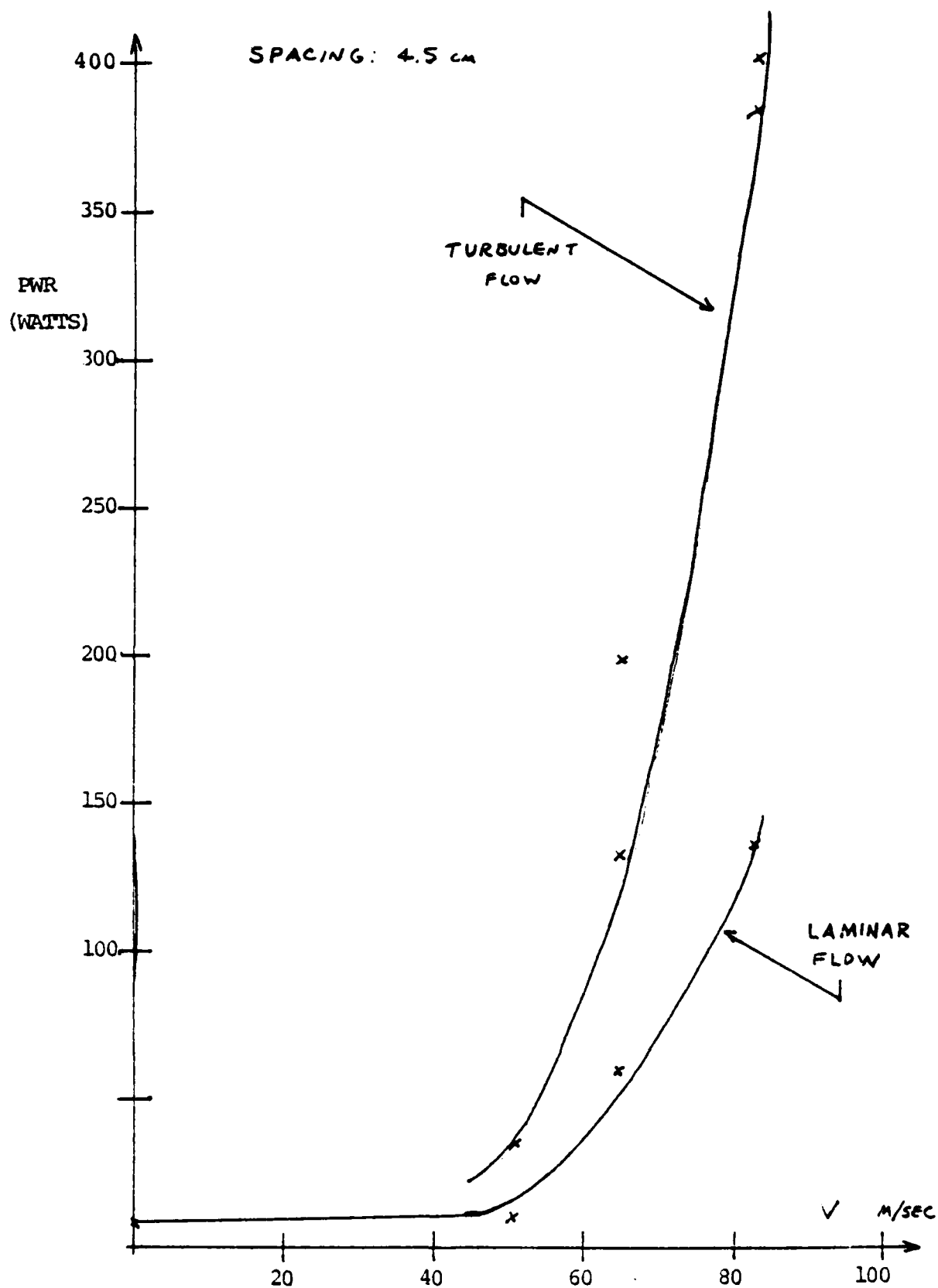
Conclusions of the previous works were verified in that the power handling capability of the flowing gas was increased with increased flow rate and was greater at each flow rate when turbulence was present in the flow.

An oscilloscope was used to measure the current through a downstream the cathode with respect to time. The results showed a series of spikes whose time density appeared to depend solely on the flow rate of the gas rather than the electrode spacing or power applied to the electrodes. This may imply a flow-related current pulsation which may ultimately be related to turbulence.

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SPACING: 2.7 cm

SPACING: 3.5 cm

SPACING: 4.5 cm

PWR (WATTS)

TURBULENT FLOW

LAMINAR FLOW

M/SEC

31

APPENDIX B

A. Sample calculations of power required to cause turbulence

At a frequency of 3kHz:

$V = 2.5 \times 10^2$ cm/sec = Turbulence "intensity"

$\lambda = 3.45 \times 10^2 / 3 \times 10^3$ = wavelength

$= 0.1$ meters $\simeq 4$ inches

Let $\zeta = 4$mm = distance between pin anodes

$\zeta = \qquad = 2 \times \pi \times f$ (4mm)

$= 0.4 \times 10^4$ cm/sec

$\cong 0.1 \times c_{sound}$

$\rho = 1$ kg/m^3 (air density at STP)

$c = 345$ m/sec (speed of sound at STP)

$\rho \times c = 3.45 \times 10^2$ kg/m^2 sec

watt = kg m^2/sec^3

Power/unit area $= (\dot{\zeta})^2 \times (\rho \times c)$

$\cong 3 \times 10^4$ W/m^2

Area $\simeq$ (5cm)^2/4 = 1.963 $\times 10^{-3}$ m^2

Power = 3 x10^4 x Area = 58.9 watts

[Reference 16]

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